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A Novel Stress-Induced Nucleation and Foaming Process and its Applications in Making Homogeneous Foams, Anisotropic Foams, and Multilayered Foams*

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SUMMARY

A new foaming process is described whereby cell nucleation and growth are induced by applying mechanical, compressive stress to a polymer-gas solution in the rubbery state. As opposed to the conventional techniques, the stress-induced nucleation has a very short induction time and occurs at relatively lower temperatures, and foams with high cell density and small cells can be made by this method. And because of the control over the nucleation and cell growth events, selective foaming can be performed to give not only homogeneous foams but also specialty foams such as anisotropic foams and image foams. At high stress levels, cell coalescence leads to multilayered foams with or without cells in the polymeric layers, and with discontinuous gaps in-between the layers.

INTRODUCTION

Recently, microcellular foams have attracted much attention due to their superior mechanical and thermal stability as compared to conventional foams with much larger cell size. The steps involved in making microcellular foams are the same as those for making conventional foams except that in the former case the cell nucleation and growth steps are carried out at temperatures in the range from the plasticized glass transition temperature T_g to a temperature slightly above the nominal T_g of the polymer. Briefly, to make microcellular foams, the polymer is first saturated with a compressed gas and then subjected to thermodynamic instability by either rapidly increasing the temperature (called the temperature soak method) or releasing the pressure (called the pressure quench method)[1]. During

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the saturation step, the pressurized gas, driven by concentration gradient, diffuses into the polymer and reaches an equilibrated state. Such a state becomes unfavourable when the system is exposed to a rapid temperature increase or pressure drop, resulting in phase separation between the gas and the polymer. This leads to nucleation of gas bubbles provided the equilibrated polymer-gas system is in the rubbery state i.e. when the processing temperature is higher than the glass transition temperature of the system. In the rubbery state, the polymer, due to its low modulus, is unable to hold the phased-out, high-fugacity gas and, therefore, undergoes local expansion as the nucleated cells grow in size. Thus, for the temperature soak method, cell nucleation and growth is achieved by heating the system from glassy state to rubbery state or heating the system from its rubbery state to a higher temperature[2-4], and for the pressure quench method, it is achieved by reducing the system pressure directly from its rubbery state[5]. Cell growth starts instantly after the cells are nucleated, and is arrested when the system temperature is lowered below its T_g.

Nucleation step is important for achieving the desired cell density and cell size. The embryonic nucleation depends on many factors such as surface tension of the polymer-gas solution, melt strength, gas solubility, pressure drop and the rate of pressure drop, and foaming temperature. Thus, for a given polymer-gas system, microcellular foams with optimum cell density and cell size can be achieved by an appropriate trade-off among the various processing parameters. Typically, microcellular foams have cells in the range 1 to 100 μm and cell density in the range 10^8 to 10^{10} cells/cm^3. Because of the rather high cell densities encountered in such foams, the nucleating agents do not make as significant a contribution in facilitating the embryonic nucleation as they do in the production of conventional foams. Nevertheless, an increase in cell density has been attributed to incorporation of micron size rubber particles in the polymer matrix[6] or due to the presence of crystallites in a semi-crystalline polymer matrix[7]. However, in either of these studies, no attempt was made to decouple the observed effect from the similar and concurrent effect caused by changing one of the processing parameters noted above.

In addition to the nucleation step, an understanding of cell growth is also important in controlling cell density and cell size. With the onset of embryonic nucleation, the cell growth starts instantly accompanied by a competition among the growing cells for the available gas in the matrix. Invariably, some of the cells do not survive past the embryonic size, while the others continue to grow until the process is quenched by rapidly cooling the system below its T_g or the T_g of the system becomes higher than the foaming temperature due to depletion of gas from the matrix. As

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a result, an optimum cell density is observed when foaming is conducted at various temperatures[1,3,8]. These considerations apply mostly for batch or semi-continuous processes. However, for extrusion-based continuous processes, cell growth is more difficult to control because the processing temperatures tend to be far above the T_g of the neat polymer. This leads to larger cells, and cell coalescence gives rise to a wider cell size distribution. A careful and controlled temperature reduction is thus required in continuous processing of microcellular foams.

Recently, we developed a new foaming process whereby nucleation is caused by applying compressive stress on the polymer-gas solution rather than utilizing the temperature soak or the pressure quench method. With our process, the nucleation occurs fast, can be induced at much lower temperatures, and the subsequent cell growth is easily controlled in a prescribed manner. Foams with much higher cell density and smaller cells can be made by the new process. In this paper, we describe the process and its applications in making homogeneous microcellular foams, heterogeneous and anisotropic microcellular foams where the foamed parts themselves are homogeneous, and multilayered foams with discontinuous gaps and with or without cells in the layers.

EXPERIMENTAL PROCEDURES

Poly(methyl methacrylate), PMMA, sheets, 2.72 mm thick, T_g = 101°C, were obtained from Canus Plastics, and 1.22 mm sheets were obtained by compression moulding. Molecular weight of the polymer was measured by GPC (Waters SEC equipped with a 401 DRI) as M_w = 108,500 and M_n = 56,700. Glycol modified poly(ethylene terephthalate), PETG, films, 0.76 mm thick, were made from Eastman's Eastar 6763 copolyester with M_n = 26,000 and Tg = 77°C. Polycarbonate, PC, Tg = 146°C, was obtained from GE Plastics (Lexan 141K-111) and was compression moulded into 1.24 mm thick sheets. Poly(ethyl methacrylate), PEMA, with Tg = 54°C and M_w = 850,000 was obtained from Aldrich, and was compression moulded into 1.22 mm thick sheets. Bone dry grade CO_2 from Praxair was used as the blowing agent.

To prepare a polymer-gas solution, the polymer sample was placed in a pressure vessel made up of stainless steel, 18 mm i.d. Swagelok VCR fittings, degassed for a few hours, and then exposed to CO_2 at a given set of temperature and pressure and for a certain period until the system reached equilibrium. The saturation pressure, temperature, and time, respectively, were 3.4 MPa/−0.2°C/24 h for PMMA, 5.8 MPa/24°C/24 h for PETG, 5.8 MPa/24°C/48 h for PC, and 2.4

MPa/–7°C/24 h for PEMA. Solubility of CO_2 in the polymer was monitored by taking out the polymer sample periodically and weighing it. This was continued until a constant weight was obtained. Saturation solubilities of CO_2 under the conditions reported above were determined to be about 22 wt% in PMMA, 12 wt% in PETG, 6 wt% in PC, and 25 wt% in PEMA. After saturation, the pressure in the vessel was released slowly, the polymer containing CO_2 was removed, and subjected to a compressive stress under ambient conditions. The moulds used were at room temperature (around 24°C) and the polymer was pressed for 5 to 30 seconds using a stress in the range from 2.1 MPa to 50 MPa, followed by quenching the sample in ice-water mixture. Parallel experiments where the saturated polymer was directly transferred from the pressure vessel into a water bath at 24°C for a certain period were also conducted for comparison.

In most cases, the compression moulds used to press the polymers had flat surfaces with straight edges. However, for making anisotropic foams, moulds with various surface patterns were used. In these cases, PMMA sheets, 2.72 mm and 1.22 mm thick, saturated with CO_2 were pressed using the moulds at 24°C under a stress of 18 to 30 MPa, followed by an ice-water quench and then degassing the matrix at about -5°C.

To determine cellular characteristics, the samples were fractured at liquid nitrogen temperature, sputter-coated with gold, and then photographed using a JEOL SEM (JSM-5300). Image Pro Plus software from Cybernetics was used to analyze the SEM photographs. Cell size and number of cells per unit area were directly obtained from the image analysis, and the number of cells per unit volume of foam (N_f) was estimated by assuming the foam to be isotropic. In what follows, the cell density is expressed as the number of cells per gram foam and was obtained by normalizing N_f with foam density determined by weighing the foam sample in air and in water. This method of expressing cell density avoids any assumption about the shape of the cell.

RESULTS AND DISCUSSION

Stress-Induced Nucleation and Foaming

Figure 1 shows a typical SEM photograph of CO_2-saturated PMMA sample, a part of which was compressed for 30 s to 22 MPa using a mould at 24°C. While the stressed part foamed immediately, the unstressed part, still saturated with CO_2, remained transparent and unfoamed. Obviously, the application of compressive stress induced cell nucleation and caused

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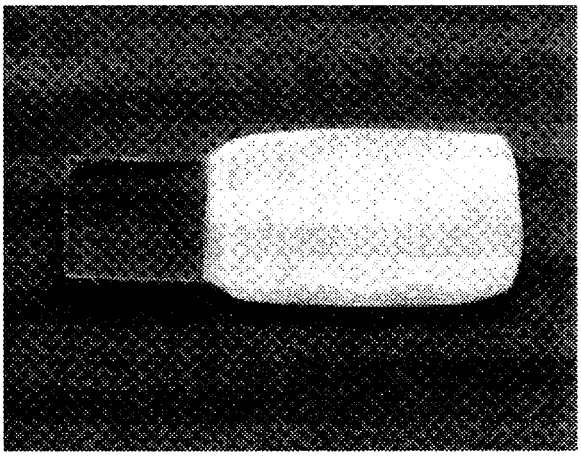
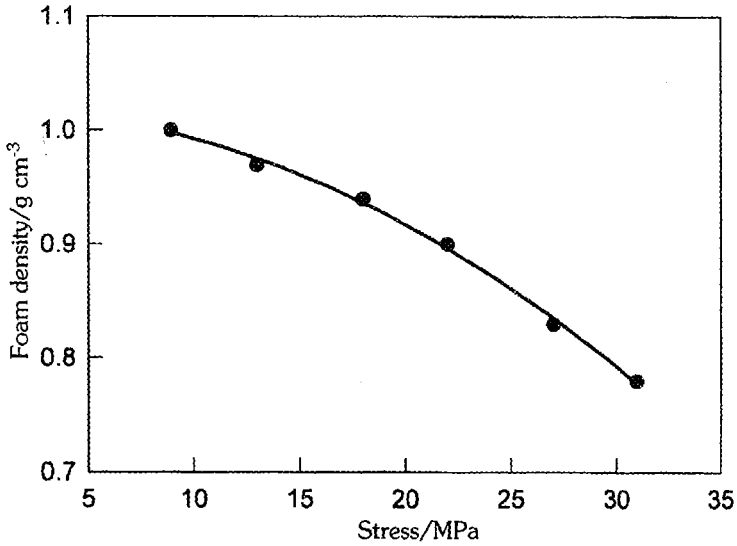
Figure 1 Photograph of a partially foamed sample made by pressing PMMA containing 22 wt% CO_2 to 22 MPa for 30 s using moulds at 24°C



the material to foam. Such stress-nucleated foaming was further explored as a function of the applied stress. The density of PMMA foams obtained by compressing PMMA containing 290 mg CO_2/gram polymer for 5 s at different stress values is shown in Figure 2. Within the stress range shown, the foam density decreases with increasing stress. It was found that at stress less than 9 MPa, foaming still occurred but on a longer time scale.

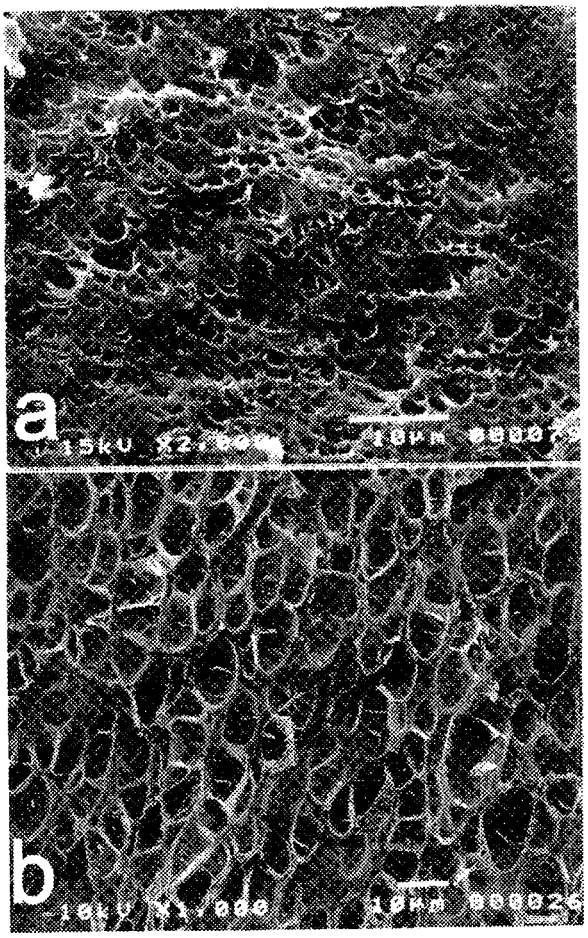
Figure 2 Density of foams made by pressing PMMA containing 22 wt% CO_2 to various stresses for 5 s using moulds at 24°C, followed by degassing below 0°C



On the other hand, foaming did not occur under a compressive stress over 35 MPa (see below).

Within a certain temperature range, the stress-induced nucleation has shorter induction time than the ones encountered in the temperature soak method. For example, as reported above, the stress-induced nucleation and foaming in PMMA occurred within a few seconds at 24°C. But, it took more than a minute for the same sample to foam when, instead of applying stress, it was transferred to a water bath at 24°C. Furthermore, the foams obtained by the two processes are substantially different in their cell structure as shown in Figure 3. The cell density and average cell size are 1.5 x 10^{11}cells/g and 2.9 μm for the stress-nucleated foam and

Figure 3 SEM photographs of foams made from PMMA containing 22 wt% CO_2 by: (a) as in Figure 1; (b) transferring the polymer-gas solution to a water bath at 24°C



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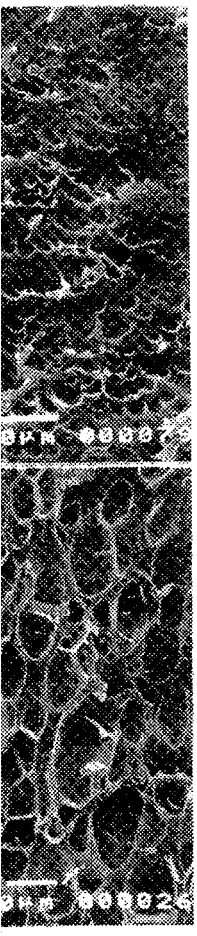
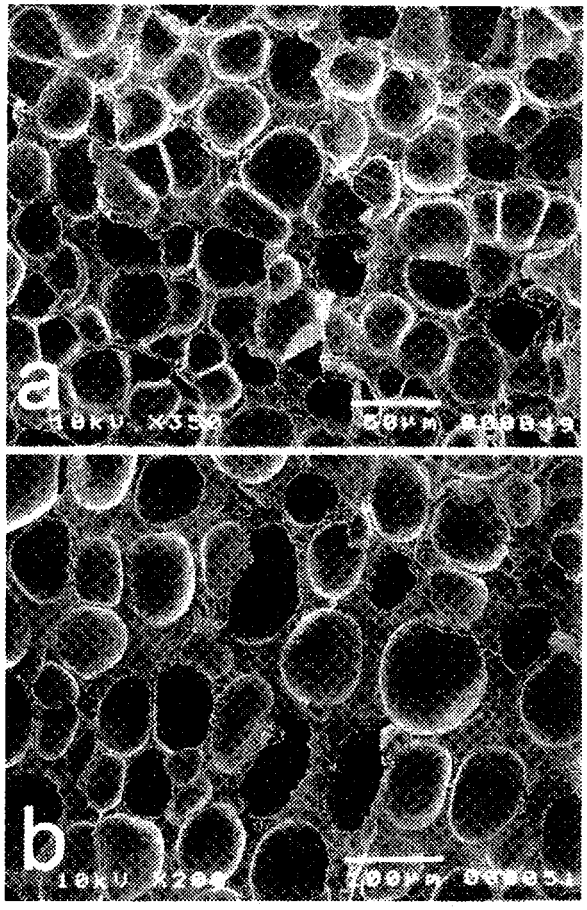


4.4×10^9 cells/g and 4.8 μm for the temperature soak-nucleated foam, and the cells appear somewhat flattened in the former case. On the other hand, when the temperature soak foaming was conducted at 35°C rather than at 24°C, cellular characteristics similar to those observed for the stress-induced foam were observed. It implies that the application of stress reduces the required foaming temperature.

Figure 4a shows the SEM photograph of a foam sample obtained by first saturating PETG with 5.8 MPa CO_2 at 24°C for 24 h, slowly releasing the CO_2 pressure, and then subjecting the polymer-gas solution to a stress of 30 MPa for 30 s at 24°C. Cell nucleation and foaming occurred instantly as the sample was stressed. For another PETG sample, saturated under the same conditions as above, the CO_2 pressure was released

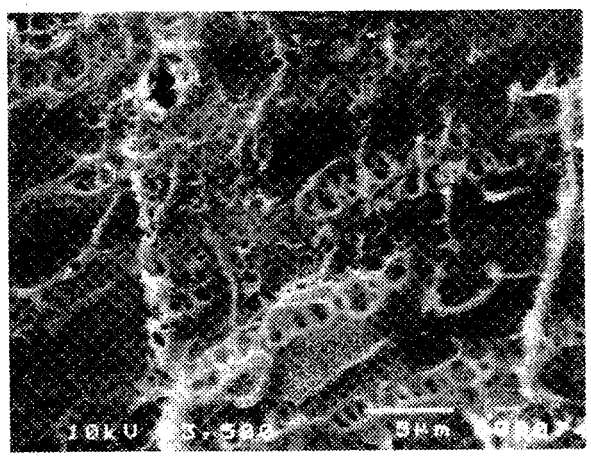
Figure 4 SEM photographs of foams made from PETG containing 12 wt% CO_2 by: (a) pressing the polymer-gas solution to 30 MPa for 30 s using moulds at 24°C; (b) by rapidly releasing the gas pressure at 24°C



rapidly to induce foaming by the pressure quench method. In this case, the sample did foam, but after a much longer time, resulting in the foam shown in Figure 4b. There is a significant difference in the cellular structures of the two foams shown in Figures 4a and 4b; the cell density and average cell size are 4.7×10^7 cells/g and 23.6 μm and 2.9×10^6 and 61.3 μm, respectively.

Figure 5 shows another example of the stress-induced polycarbonate foam. The polymer was saturated with 5.8 MPa CO_2 at 24°C, and then subjected to 32 MPa stress under ambient conditions. As seen in Figure 5, the sample was only partially foamed, containing sub-micron size cells. On the other hand, the unstressed sample showed no cellular structure – the sample simply degassed gradually over a long period. It should be noted that under the saturation conditions used in this work, PMMA-CO_2, PEMA-CO_2, and PETG-CO_2 are in the rubbery state[1,8] which facilitates the cell nucleation and growth processes whereas PC-CO_2 is in the glassy state[9] which retards cell nucleation.

Figure 5 SEM photograph of a foam made by pressing PC containing 6 wt% CO_2 to 32 MPa for 30 s using moulds at 24°C



Embryonic nucleation is a stochastic phenomenon. Accordingly, an exact and detailed account of the fluctuations that lead to nucleation are difficult to model. Here, we will not attempt to model the stress-induced nucleation and foaming process, but choose to rationalize the observed phenomenon in simplistic, thermodynamic terms. A schematic of the effect of hydrostatic pressure on a polymer-gas system, where the polymer is present in excess, is given in Figure 6. Consider a piston-cylinder assembly, Figure 6a, initially containing a two-phase polymer-gas

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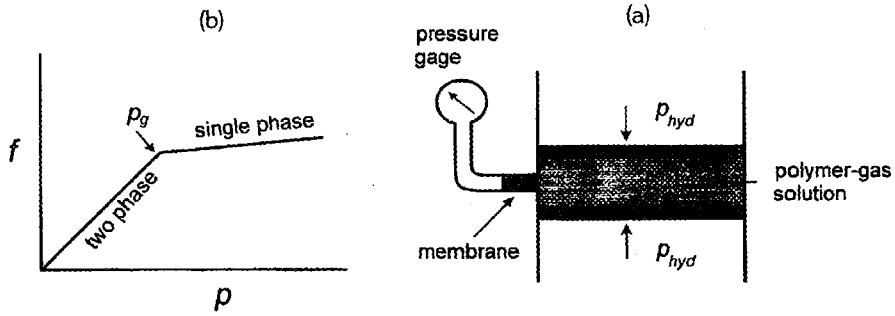
Figure 6 Schematics of the effect of applied stress on a polymer-gas system



system at a constant temperature. As the system is compressed, the gas pressure increases and this forces more gas in the polymer phase. This will continue until the gas phase is depleted and the piston is just touching the single-phase polymer-gas solution – the scenario shown in Figure 6a. The fugacity f of the dissolved gas will follow the two-phase line (Henry's law), as shown in Figure 6b, up to the point p_g where the gas phase disappears; p_g corresponds to the hydrostatic pressure p_{hyd} in Figure 6a. On further compression of the polymer-gas solution, the fugacity of the dissolved gas will increase along the single-phase line as dictated by the Poynting correction[10]. This increase in fugacity can be measured in a hypothetical experiment, Figure 6b, where the gas-saturated polymer phase is connected to a pressure gage via a membrane plug permeable to gas but not to macromolecules. The pressure recorded on the gage will be higher than p_g. Such an observation, in fact, has been made experimentally on liquid-gas systems[11] and theoretically on solid-gas systems[12].

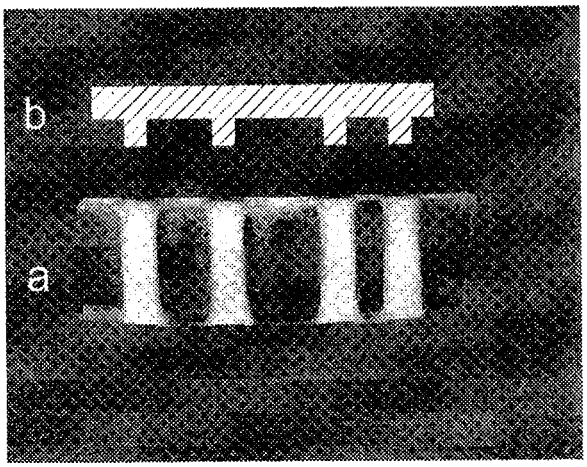
These considerations imply that under the external stress, the raised fugacity of the dissolved gas beyond its equilibrium fugacity – corresponding to p_g – will lead to nucleation in a gas-saturated polymer when the system is in the rubbery state.

Anisotropic Foams

The stress-induced foaming process can be used to produce anisotropic foams with a predefined structure because the polymer-gas system can be compressed in a controlled and selective manner. As noted above, the cell-nucleation induction time and foaming temperature are considerably lower in the stress-induced foaming process than in the temperature soak or the pressure quench process. It implies that a processing temperature

can be chosen so that only the stressed part will foam within a certain time, leaving the rest of the polymer unfoamed. Figure 1 is an example of selective foaming. An extension of this concept is shown in Figure 7. The rib foams shown in Figure 7a were made by pressing CO_2-containing PMMA at 24°C using a mould with the comb pattern shown in Figure 7b, followed by degassing the material at a temperature below the glass transition temperature of the polymer-gas system[1]. Such a structure is stronger than the totally foamed material, and could show stiffness advantage over the neat polymer along the rib direction when the ribs are dense enough. This conjecture is based on the assumption that the foamed parts do not take any load but simply act as bonds in between the unfoamed parts which now have a high ratio of height to width.

Figure 7 Photographs of rib foam (a) obtained by pressing PMMA containing 22 wt% CO_2 with the mould (b)



This technique to produce an integrated, anisotropic structure with the desired combination of foamed and unfoamed parts makes it possible to produce low-weight articles with good mechanical properties. That these are desirable traits is evident in the naturally occurring cellular materials such as trees and bones. These materials have anisotropic cellular structure and are widely used for functional as well as structural applications[13,14]. Man-made, laminated honeycomb-core and foamed-core sandwiches are also examples of successful applications of anisotropic foams as structural materials[15]. Generally, the existence of voids in a solid matrix deteriorates its mechanical properties. Although such an effect can be reduced by decreasing the cell size, the improvement is quite limited.

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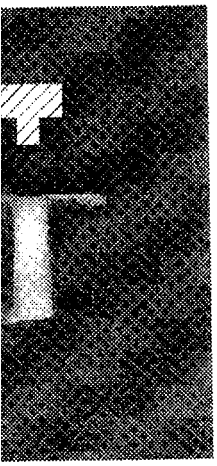

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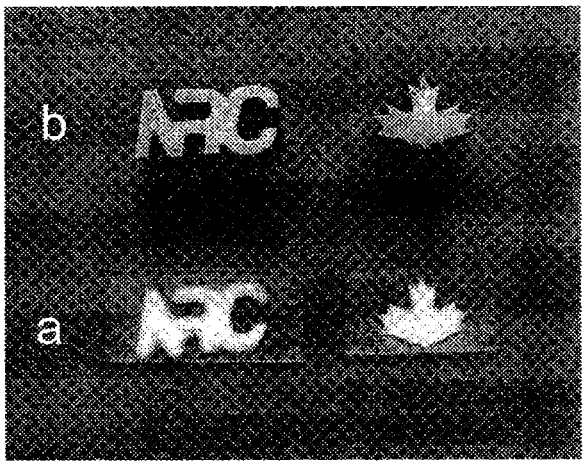
On the other hand, incorporation of unfoamed parts can compensate for the loss in mechanical properties of cellular materials provided due consideration is given to the size, shape, and distribution of the foamed and unfoamed parts.

It is also possible to design anisotropic foams for functional applications. Figure 8 shows an example of image foams made by the stress-induced foaming method. Here, moulds with the patterns of maple leaf and NRC logo, Figure 8b, were used to press the CO_2-saturated PMMA sheets. The stressed parts foamed instantly reflecting complete image transference, Figure 8a, while the unstressed parts remained unfoamed and transparent. The bubble cells in the foamed parts scatter visible light, thus providing the image contrast. Again in these image foams, the foamed parts are an integral part of the transparent polymer matrix.

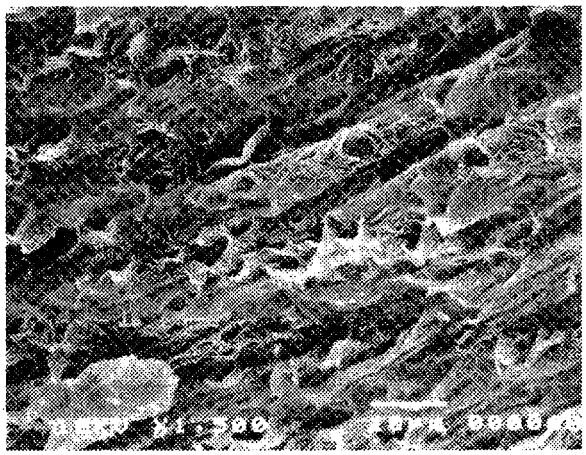
Figure 8 Photographs of image foams (a) obtained by pressing PMMA containing 22 wt% CO_2 with the moulds (b)



Multilayered Foams

As reported in Figure 2, within a certain stress range, the gas saturated polymers in the rubbery state responded instantly to the applied stress to give foams. However, we found that at elevated stress levels, the resulting foam had a layered morphology. Figure 9 shows a multilayered foam obtained by pressing CO_2-saturated PMMA under a stress of 37 MPa at 24°C. The foam is composed of layers with discontinuous gaps and elliptical cells. The layers are less than 10 μm thick, typically around 4 μm thick. In extreme cases, when the stress applied to the polymer-gas solution is sufficiently high, the bubble cells get totally excluded from the

Figure 9 SEM photograph of a layered foam with elliptical cells obtained by pressing PMMA containing 22 wt% CO_2 to 37 MPa with 24°C moulds



layers. As shown in Figure 10, fine PEMA-layers, free of bubble cells, were obtained when the polymer containing CO_2 was pressed at 50 MPa. The layers are less than 1 μm thick, and, again, are separated by discontinuous gaps.

A schematic of the process to produce multilayered foams is shown in Figure 11 Starting with a homogenous solution of polymer and gas, the application of stress leads to instant nucleation, followed by cell growth that occurs preferentially in the plane perpendicular to the stress direction.

Figure 10 SEM photograph of a layered foam without any cells but with discontinuous gaps obtained by pressing PEMA containing 25 wt% CO_2 to 50 MPa with 24°C moulds.

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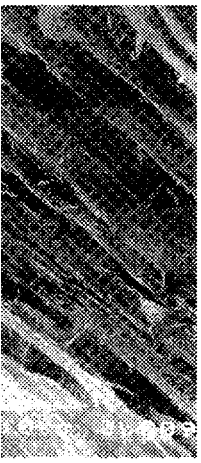
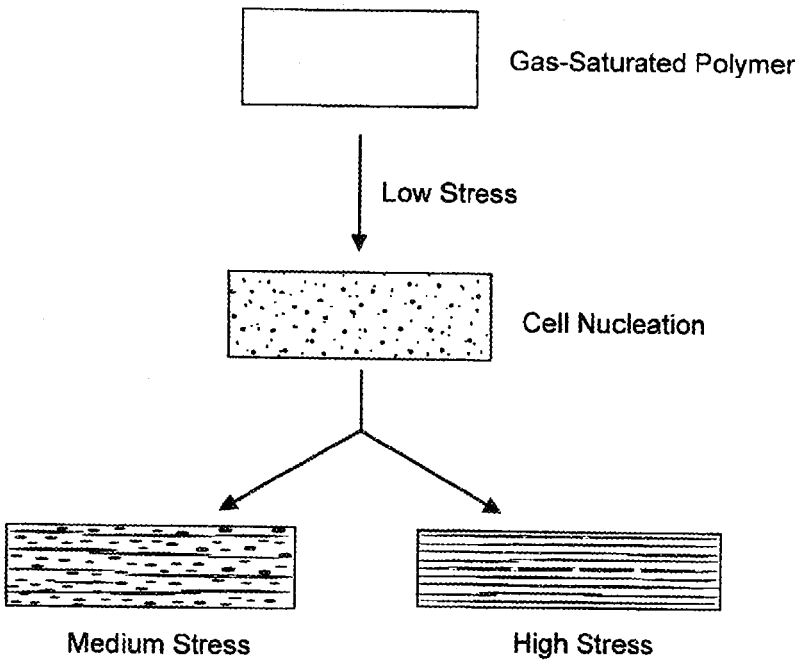


Figure 11 A schematic of the layered-morphology development in a polymer-gas solution subjected to elevated stress. The dark and the white parts represent gas and polymer phases, respectively. Layers with discontinuous gaps and elliptical cells are obtained at medium stress levels; cell-free layers with discontinuous gaps are obtained at high stress levels



At low stress levels, homogeneous, microcellular foams with somewhat flattened cells result (see Figure 3a). At medium stress levels, some of the cells coalesce in the preferential direction and get partially interconnected, thereby giving a layered foam containing elliptical cells and discontinuous gaps. At high stress levels, cell coalescence in the preferential direction continues leading, eventually, to a multilayered structure with discontinuous gaps running along the direction perpendicular to the applied stress, and the layers no longer contain any bubble cells. The applied stress and the viscosity of the polymer-gas system play vital roles in affecting the resulting morphology. Both high stress and low viscosity favour formation of cell-free layers.

It should be noted that in multilayered foams the polymer is significantly oriented due to deformation of the rubbery polymer-gas system under stress. Although the orientation in such materials is difficult to measure due to presence of bubbles and air-filled gaps, our preliminary experiments show that multilayered foams made by the technique reported here are much stronger than the foams made by other techniques. Furthermore,

in the production of multilayered foams, polymer deformation is accompanied by phase separation and gas expansion. At high stress levels, the escaping gas acts as an interlayer lubricant resulting in almost the same amount of deformation for each layer, Figure 10. It implies that the macromolecular orientation in each layer of the foam is possibly the same.

CONCLUSION

There are distinct advantages of the stress-induced nucleation and foaming process over the conventional techniques of temperature soak or pressure quench process used in batch, semi-continuous, or continuous production of foams. The stress-induced process can be adopted for any of these three manufacturing technologies. As opposed to the conventional techniques, the induction time to nucleate cells is much shorter in the stress-induced foaming process. Furthermore, the cells can be nucleated selectively whereas in the conventional techniques, nucleation occurs throughout the entire body of the polymer. The stress-induced foaming process provides control not only during the nucleation stage but also during the cell growth stage which is quenched instantly as soon as the stress is removed. The quenching process is further facilitated by the fact that the foaming is done at relatively lower temperatures. However, in the conventionally used techniques, it takes a finite time before the polymer is quenched to a temperature below the T_g of the system to arrest cell growth. In addition, the stress-induced foaming process is highly versatile as it can be used to produce not only homogeneous foams but also anisotropic or heterogeneous foams, and multilayered foams with or without cells in the polymer layers.

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REFERENCES

1. Handa Y.P. and Zhang Z., J. Polym Sci.: Part B: Polym. Phys., 38, (2000) 716; and US Patent No. 5,955,511 (1999)
2. Kumar V. and Suh N.P., Polym. Eng. Sci., **30**, (1990) 1323
3. Kumar V. and Weller J., J. Eng. Industry, **116**, (1994) 413.
4. Park C.B. and Suh N.P., J. Manu. Sci. Eng., **118**, (1996) 639

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Sci. Eng., **118**, (1996) 639

5. Goel S.K. and Beckman E., J. Polym. Eng Sci., **34**, (1994) 1137
6. Ramesh N.S., Rasmussen D.H. and Campbell G.A., Polym. Eng. Sci., **34**, (1994) 1698
7. Baldwin D.F., Shimbo M. and Suh N.P., Trans. ASME, **117**, (1995) 62
8. Handa Y.P., Wong B., Zhang Z., Kumar V., Eddy S. and Khemani K., Polym. Eng. Sci., **39**, (1999) 55
9. Zhang Z. and Handa Y.P., J. Polym. Sci.: Part B: Polym. Phys., **36**, (1998) 977
10. Prausnitz J.M., Lichtenthaler R.N. and de Azevedo E.G., Molecular Thermodynamics of Fluid-Phase Equilibria, Prentice-Hall, Englewood Cliffs, New Jersey, 1986
11. Enns T., Scholander P.F. and Bradstreet E.D., J. Phys. Chem., **69**, (1965) 389
12. Handa Y.P., J. Phys. Chem. **94**, (1990) 2652
13. Wangaard F.F., Wood: Its Structure and Properties, The Pennsylvania State University, University Park, PA, 1979
14. Gibson L.J. and Ashby M.F., Cellular Solids Structure and Properties, Cambridge University Press, 1997
15. Allen H.G., Analysis and Design of Structural Sandwich Panels, Pergamon press, Oxford, 1969